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Woven type smart soft composite for soft morphing car spoiler

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ABSTRACT

Morphing structures making use of smart materials are considered to be a promising technology for the amelioration of the aerodynamic performance of land and air vehicles. In particular, soft morphing structures are capable of continuous curvilinear structural deformation upon actuation without discrete sections that generate aerodynamic losses. In this paper, a woven type smart soft composite consisting of shape memory alloy wires and glass fiber-reinforced composite was fabricated and applied to the rear spoiler of a $^1/_8$-scaled radio-controlled car which is capable of actuating either symmetrically or asymmetrically. To verify its aerodynamic performance, wind tunnel experiments were carried out using a stand-alone spoiler under various wind speeds, angles of attack, and actuation modes. First, the results of the symmetric mode of actuation intended for braking conditions are presented. Second, to generate a yawing moment to assist the vehicle in cornering, the asymmetric mode of actuation was tested in an open-circuit blowing-type wind tunnel. Results of the symmetric and asymmetric modes of actuation were then compared with a symmetric airfoil (NACA 0010) with a flap tested under the same conditions. Lastly, the spoiler was mounted on the small-scale car and wind tunnel tests were conducted to determine the potential of augmentation on aerodynamic performance by implementing the soft morphing spoiler.

1. Introduction

The driving performance of ground vehicles is influenced by various factors that can be characterized as external or internal to the body. To improve efficiency, the fundamental elements of the internal structure of a car have been researched extensively, including the internal combustion engine, the steering apparatus, and the power train. However, for a long time, the aerodynamic properties of cars were not recognized as a significant factor in car performance. Since the 1960s, car aerodynamics, which was affected as the car exterior evolved, became a crucial and low-cost technology that could lead to better vehicle performance as other features reached a mature stage [1,2]. In driving, friction-like forces, including the downforce generated by the moving vehicle, have a considerable effect on the performance of the vehicle in terms of braking, cornering, and acceleration. These forces are related to the vertical load and friction coefficients of each tire. By modifying the external shape of the vehicle, the adhesion forces on the tires related to the normal force of the vehicle with the ground can be controlled to improve running ability in cornering and braking. Especially, wings mounted on vehicles have been used primarily to apply aerodynamic forces to increase the downforce exerted on the tires without increasing the vehicle's weight with minimal drag [1–3].

A spoiler is an aerodynamic device that is used to generate aerodynamic forces using the airflow over the vehicle. Specifically, a rear spoiler diffuses airflow, minimizing vortexes at the rear of the vehicle while inducing downward pressure. To improve the aerodynamic efficiency of vehicles using spoilers, various types of spoilers have been investigated. With respect to the shape of the spoiler, fundamental research has been performed on shapes ranging from flat panels to inverted airfoils [4]. Studies of single-element wings including NACA airfoil were performed using computational fluid dynamics (CFD) analyses and wind tunnel experiments considering diverse ground effects (i.e., moving ground and fixed ground) [5–10]. Furthermore, multi-element

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wings with deflecting parts such as flaps to reinforce air-induced forces were investigated [11–16].

Recently, various types of morphing wings for aerial vehicles have been investigated to improve efficiency over a wider range of flight environments by changing its shape to adapt to the vehicle's running condition [17,18]. To realize the morphing mechanism, smart materials such as shape memory materials and piezoelectric materials or adaptive structures were used to change the shape of the system [19–21]. Shape memory materials are characterized by the ability to recover their shape after deformation under specific conditions [22]. Among the shape memory materials, shape memory alloy (SMA) materials are widely used in the design of shape memory structures due to their superelasticity, their high power to weight ratio, and also due to their shape memory effect [23]. In the aerospace field, many of SMA applications are intended to amplify aerodynamic performance using deformable wings while reducing the complexity of the actuating system [24]. Analysis on the capability of adaptive wings consisting of sandwich structures, flexible ribs, and a flexible skin was simulated to determine whether SMA devices can generate enough force to realize the deformation of the wings [25]. A morphing wing was controlled using shape memory alloy actuators to improve the aerodynamic efficiency of the wing in terms of the lift-to-drag ratio (C_L/C_D) and laminar flow extension over the upper surface of the wing with a hardware-in-the-loop control strategy [26]. SMA actuators were used to create a discretized curvature approximation in the hyperelliptical cambered span wing inspired by the bird morphology [27]. To store the elastic energy and to obtain a larger deformation than by using SMA wires, SMA springs were used for a changeable skin of the wing [28]. To be used for a twist morphing wing, a soft morphing actuator capable of twisting motion using a pair of SMA wires was investigated [29]. Also, smart soft composite (SSC) actuators in which smart materials and anisotropic materials are embedded together in an elastomer was presented to with a coupled in-plane/bending/twisting deformation of the structure [30]. The SSC is categorized by its composition of anisotropic materials that exert an influence on actuation as a scaffold type and a woven type. The performance characteristic of each types of the SSC was evaluated and multiple applications have been presented [31–34].

This study looks at the design and fabrication of a soft morphing structure to be used as a small-scale car spoiler following previously researched morphing wing concepts in order to improve the aerodynamic efficiency using a compact system [17–21]. Since car spoilers are similar to airplane wings in form and function, morphing wing concepts could also be applied to spoilers in order to improve the driving performance further than with current mechanical spoiler systems. In the study, a new type of soft morphing spoiler was developed and evaluated to determine its aerodynamic performance in terms of the negative C_L/C_D and yawing moment. For the morphing part, a woven type SSC consisting of SMA wires and glass fibers woven together within a polydimethylsiloxane (PDMS) matrix was fabricated and implemented as a spoiler similar to a deflectable flap. Using the woven type SSC, the morphing spoiler achieved a large deformation at the trailing edge of the spoiler, and both a symmetric and asymmetric bending deformation of the spoiler were generated depending on which SMA wires were actuated. The aerodynamic characteristic of the spoiler was verified under various conditions of wind speeds, angles of attack, and actuation modes using an open-circuit blowing-type wind tunnel. Furthermore, wind tunnel experiments were conducted to compare the morphing spoiler with a symmetric airfoil, NACA 0010 with a flap, which has a deflecting element at the rear of the airfoil. Finally, the soft morphing spoiler was mounted on the small-scale vehicle and the effect of its actuation on the aerodynamic performance was measured through wind tunnel testing.

2. Woven type smart soft composite

2.1. Concept

In the present study, the soft morphing part is composed of a shell type actuator based on a woven type SSC with embedded SMA wires to realize the 3D deformation of a large area. The woven type SSC consists of a glass fiber-reinforced smart actuator made from commercially available SMA wires (Ni: 55 wt%, Ti: 45 wt%; Dynalloy, Inc.) and glass fibers interwoven using a plain weave method. The SMA wires were used as an actuator to realize the deformation of the structure, and the anisotropic properties of the glass fibers were used for controlling the direction of the deformation by changing the disposition of the embedded fibers.

To fabricate the woven type SSC, the SMA wires were first positioned on the loom in the lengthwise direction, and then glass fibers were interwoven perpendicularly with the SMA wires. The fabricated woven structure was then combined with PDMS (Sylgard 184, Dow Corning), a soft polymer with isotropic properties, and cured in a temperature-controllable oven. Before curing the composite structure, additional layers of glass-fiber fabric were layered on the woven structure such that the SMA-embedded active layer was positioned eccentrically from the neutral plane. The behavior characteristics of the SSC structure are affected by the stacking order, number, and orientation of the glass-fiber fabric and woven layers, and allows for modifying the mechanical properties and deformation quantity of the actuator to achieve a desired performance. Fig. 1 shows the concept of the woven type SSC, and the typical material properties of the glass fiber and the PDMS are shown in Tables 1 and 2.

2.2. Active component of woven type smart soft composite

To generate a deformation of the woven type SSC, SMA wires are used by applying electric currents selectively to SMA wires embedded in the soft matrix. The use of SMA as an actuator is advantageous in implementing complicated movements that demand lightweight, large force, and a simple system. In particular, soft or compliant actuators based on non-traditional materials, including SMA, have been developed to achieve novel motions that have been of particular interest for morphing applications [35–37].

The SMA wires can be contracted in their axial direction through Joule heating and then relaxed by cooling them. When the SMA wires are heated over the phase transformation temperature, a contractile force is generated which deforms the surrounding matrix. After the SMA wire cools down to below the phase transformation temperature, the structure recovers its original shape due to the elastic recovery force of the structure. In this case, the woven type SSC uses the thermal shape memory effect of SMA in two reversible stable phases, austenite and

Table 1
Material properties of the glass fiber (E-glass fiber, KPI Co., Ltd).

Parameter	Value (unit)
Tensile strength	1470 MPa
Specific gravity	2.54
Max. elongation	4%
Softening point	846 °C